

ARMY RESEARCH LABORATORY



"Clean Burning" Low Flame Temperature Solid Gun Propellants

Rose A. Pesce-Rodriguez

Robert A. Fifer

Joseph M. Heimerl

ARL-TR-1072

April 1996

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

19960425 014

DATA QUALITY IMPROVED 1

NOTICES

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)			2. REPORT DATE April 1996	3. REPORT TYPE AND DATES COVERED Final, Oct 94-May 95
4. TITLE AND SUBTITLE "Clean Burning" Low Flame Temperature Solid Gun Propellants			5. FUNDING NUMBERS PR: 1L161102AH43	
6. AUTHOR(S) Rose A. Pesce-Rodriguez, Robert A. Fifer, and Joseph M. Heimerl				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WT-PC Aberdeen Proving Ground, MD 21005-5066			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-1072	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) In an attempt to eliminate nitrogen oxides (NOx's) from the combustion and pyrolysis products of solid propellants, an investigation into the use of "De-NOx" agents was performed. The agents selected were all compounds that thermally decompose to generate amines; participation of amines in the thermal De-NOx process results in the reduction of nitrogen oxides to nitrogen. Of all the compounds screened, it was found that urea was the best suited for use as a De-NOx agent in solid gun propellants. Use of urea resulted in a significant decrease in NOx production. Furthermore, urea is thermally stable up to a temperature of 130° C, and is compatible with nitrocellulose-based formulations. Compared to neat JA2 (a double-base propellant), a JA2/urea formulation containing 10 weight-percent urea generates 60% less NOx. Calculations indicate that the incorporation of 4% urea results in a 200 K decrease in flame temperature, and a decrease in impetus and velocity of approximately 4% and 2%, respectively.				
14. SUBJECT TERMS clean burning, solid propellant, flame temperature, gun barrel erosion, urea, De-NOx, nitrogen oxides			15. NUMBER OF PAGES 22	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENT

The authors would like to thank Mr. Ron Simmons (Naval Surface Warfare Center, Indian Head Division), Dr. Anthony Kotlar (Army Research Laboratory [ARL]), and Dr. William Anderson (ARL) for useful discussions.

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENT	iii
LIST OF FIGURES	vii
1. INTRODUCTION	1
2. BACKGROUND	2
3. EXPERIMENTAL	3
3.1 Samples	3
3.2 Chromatographic Instrumentation	4
3.3 Pyrolysis Experiments	4
3.4 Thermal Analysis	4
3.5 Calculations	5
4. RESULTS AND DISCUSSION	5
5. CONCLUSION	8
6. REFERENCES	11
DISTRIBUTION LIST	13

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.	The Miller and Boman thermal De-NOx mechanism	2
2.	Structure of candidate De-NOx agents	4
3.	NO produced by JA2/urea propellant (pyrolysis products, by GC-MS, equilibrium combustion products, 0.2 g/cm ³ nominal gas phase density (scaled to match NO produced at 0 wt-% urea for relative comparison)	6
4.	Calculated flame temperature for JA2/urea propellant; from Blake calculations at 0.2 g/cm ³ nominal gas phase density	7
5.	Calculated impetus for JA2/urea propellant; from Blake calculations at 0.2 g/cm ³ gas phase density	7
6.	DSC thermograms for JA2 and JA2/urea propellant (little/no change in exotherm temperature observed, indicative of good compatibility)	8

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

Incomplete combustion of solid gun propellants is a common occurrence during the firing of both experimental and fielded gun systems. Included among the products of this phenomenon are nitrogen oxides (NO_x) and carbon monoxide (CO). CO poses the most serious health hazard (Weyandt and Ridgeley 1993), and can be found at such dangerously high levels that health agencies may impose restrictions on the number of test firings that can be performed per day. Unfortunately, elimination of CO from gun propellant combustion products is not feasible from a ballistic standpoint. However, the corrosive nature of nitrogen oxides (NO_x's where x = 1,2) also make them a matter of concern for both users and environmental and health-related agencies. Snelson et al. (1989) measured breech NO_x concentrations that were 10⁵ times greater than predicted by thermochemical calculations, indicating that the actual problem may be more serious than suggested by equilibrium calculations. While it may be argued that bore evacuators protect tank crews against toxic combustion products, this is true only when the evacuators are functioning properly and are intact. It has been reported that a hole as small as 2 cm is sufficient to allow dangerously high levels of toxic gases into the crew compartment. It has been suggested that even intact evacuator systems do not keep tank compartments free of propellant combustion gases. Exposure of test crews to combustion gases is becoming increasingly more common as test site personnel resort to enclosed (muffled) bays to reduce noise levels near urban populations. At such sites, large fans must ventilate the test bay for several minutes to remove toxic vapors before workers can enter the test area.

Solid residues resulting from incomplete combustion also pose significant safety and environmental concerns. For example, smoldering residues remaining after firing often result in significant quantities of smoke. This low pressure pyrolysis generates much larger quantities of NO_x and other nonequilibrium gases than does high pressure combustion. Re-ignition of propellant residue in fielded tanks has been reported (Wren 1993). Propellant residue in breeches is also said to be responsible for the creation of sealing problems (Rinaldi 1993).

As discussed above, incomplete combustion of solid propellants can pose a significant hazard to the health and safety of military and civilian personnel. The work presented here is intended to address and reduce this hazard by identifying solid propellant formulations that will burn more cleanly and more completely than current formulations.

2. BACKGROUND

It has been known for some time that M30 gun propellant (composed of nitrocellulose, nitroguanidine and nitroglycerine) differs from other NC-based propellant in that its flame lacks a "dark zone" (i.e., it does not have a nonluminous zone) (Vanderhoff 1988, 1989, 1991; Vanderhoff, Teague, and Kotlar 1992; Teague, Singh, and Vanderhoff 1993). Dark zone chemistry is dominated by the chemistry of NO, specifically, by the slow conversion of NO to N₂ (Vanderhoff, Teague, and Kotlar 1991). Much attention has been given to this chemistry because of its potential importance to delayed ignition (Vanderhoff, Teague, and Kotlar 1991, 1992). It was proposed by Anderson (1987) that the absence of the dark zone in M30 might suggest that nitroguanidine was behaving as a "De-NOx agent" (i.e., a species capable of reducing NOx to N₂).

A proposed mechanism for the removal of NO and, hence, NOx's, by amines is described in Figure 1 (Miller and Bowman 1989). The essence of this process is the consumption of NO in reaction paths that lead ultimately to N₂. Note that NH₃ does not react with NO (the reaction is endothermic by 60 kcal/mole).

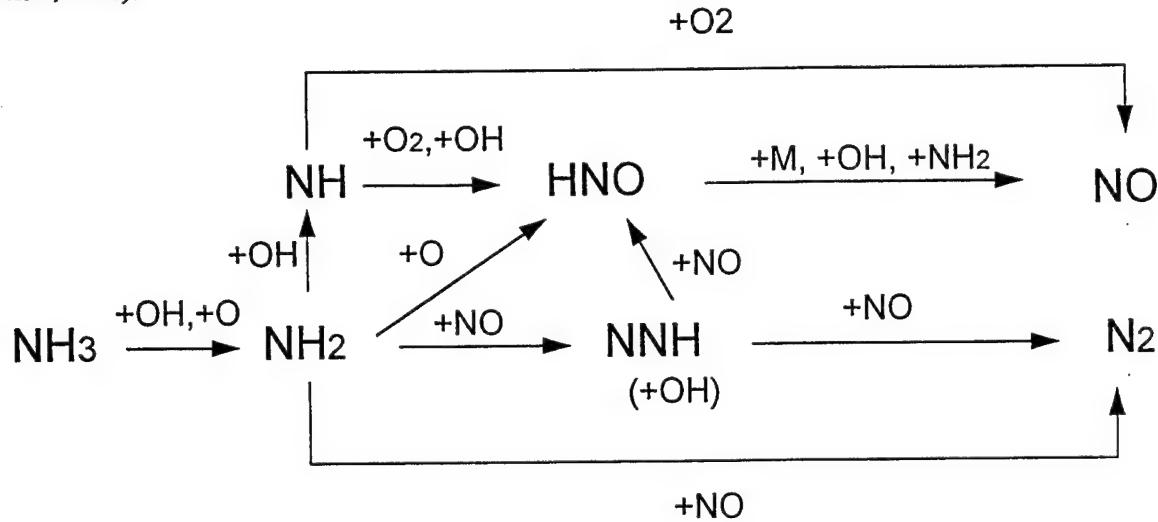


Figure 1. The Miller and Boman thermal De-NOx mechanism.

De-NOx agents have been shown to be effective in eliminating NOx production in internal combustion engines and other devices. In these applications, the agents are ammonia- or amine-producing species that reduce NO to N₂. In nitrate ester- or nitramine-based solid gun and rocket propellants, NO is produced from the -NO₂ groups in the energetic oxidizer (e.g., RDX), polymer (e.g., nitrocellulose NC), or plasticizer (e.g., nitroglycerine, NG). The concept for the current work is based on the use of De-NOX

agents in solid propellants to reduce NO to N₂ at or near the burning propellant surface; the increased near-surface energy release should also lead to more complete combustion (i.e., more equilibrium products and less solid residue) and reduction of other products of a toxic or carcinogenic nature. In addition to reducing NOx levels in the combustion products of solid gun propellants, burn rate modification by De-NOx agents is also possible. Previous attempts to "catalyze" the burning of solid propellants have made use of oxidizing agents (e.g., PbO), rather than reducing agents (e.g., NH₃). (Note: an exception to this has been found [Fifer and McBratney 1983; Fifer and Cole 1980].) If De-NOx agents can effectively eliminate NOx from the combustion products of solid propellants, they may also serve as effective burning rate "catalysts," thereby simultaneously preventing pollution (by both NOx and heavy metals) and enhancing performance.

Based on this background information, an investigation into the effects of ammonia- and amine-generating compounds on solid propellant combustion and pyrolysis products was undertaken. In an examination of the pyrolysis products of M30 (a triple-base propellant) and two "nitroguanidine-free" nitrocellulose-based propellants (M9 and M10, double- and single-base propellants, respectively), it was observed that M30 actually generates more NO than do the propellants without nitroguanidine. These results suggest that while nitroguanidine might participate in the elimination of NO under high pressure combustion conditions, it does not do so at atmospheric pressure. Results presented in this report indicate that while nitroguanidine does generate NH₃, it also generates significant quantities of NO and is therefore an unsuitable De-NOx agent.

The specific focus of the present work is on the use of urea as a De-NOx agent, especially under pyrolysis conditions where traditional coolants such as nitroguanidine appear to be ineffective. While this application may be new, a survey of the literature reveals that use of urea as a stabilizer in solid propellants is not. In the 1980s, urea was used as a stabilizer in certain double-base propellants. The propellants were invented by Hudson Maxim in collaboration with R. D. Schüpphaus, and were known as "Maxim-Schüpphaus Powders." The propellants also have the distinction of being the first manufactured in the form of multiperforated grains. Formulations typically contained 0.5–1.0 wt-% urea (Kaye 1978).

3. EXPERIMENTAL

3.1 Samples. Experimental quantities of a double-base, JA2-like solid propellant were fabricated by handmixing acetone solutions of JA2 with ground urea. Pyrolysis samples were prepared by casting films

of the handmixed propellants on aluminum foil. Candidate De-NOx agents included triaminoguanidine nitrate (TAGN), nitroguanidine (NQ), triamino-trinitro-benzene (TATB), ammonium carbonate, and urea. Structures of these compounds are given in Figure 2.

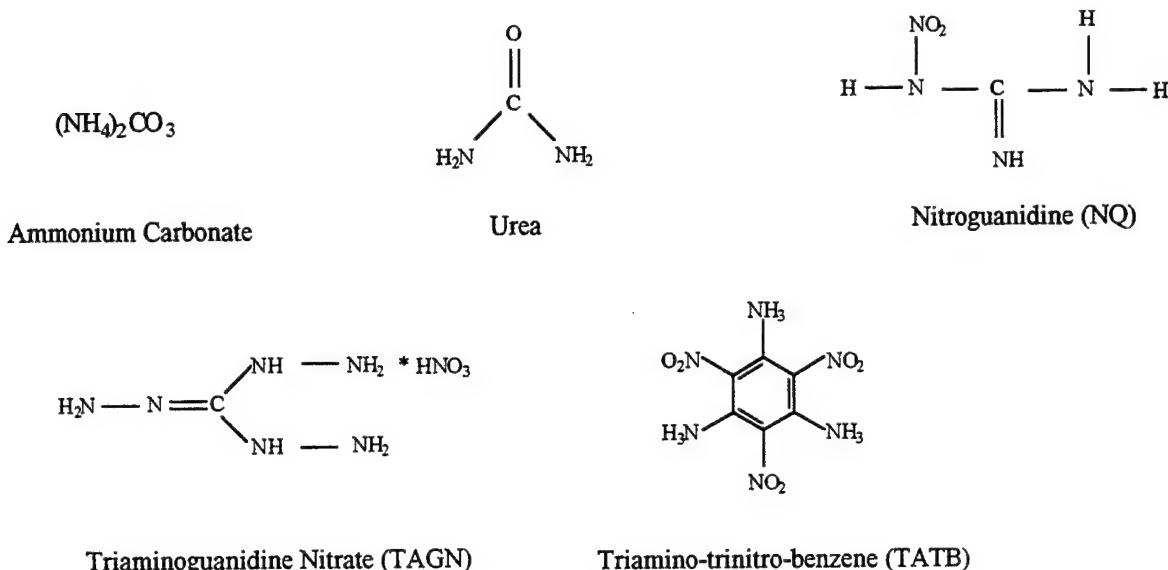


Figure 2. Structure of candidate De-NOx agents.

3.2 Chromatographic Instrumentation. Analyses of pyrolysis products were conducted using a Hewlett Packard 5965 gas chromatograph (GC) interfaced to a Hewlett Packard Model 5965A infrared detector (IRD), and 5970 mass spectrometric detector (MSD). Only MS results are reported here. Chromatographic conditions: Quadrex capillary column 0.32-mm \times 25-m \times 3- μm OV-17 film; oven program: 50° C for 3 min, then 50° C to 200° C at 10°/min; injector and interface chamber held at 200° C.

3.3 Pyrolysis Experiments. Samples were placed in quartz tubes and held in place with plugs of glass wool. Tubes were inserted into a coil-type Pyroprobe (Chemical Data Systems [CDS], Model 122) that was connected via a heated CDS interface chamber to the splitless injector of the GC. The heated GC interface was continuously swept with helium carrier gas. Approximately 0.6 mg of sample was pyrolyzed for each analysis. All samples were pulse-pyrolyzed at 1,000° C.

3.4 Thermal Analysis. Differential scanning calorimetry (DSC) was performed using a Mettler DSC 30 calorimeter interfaced to a Mettler TC10A processor. The heating rate was 10° C/min. Samples were

placed in crimped aluminum pans with three pin holes punched through the cover. Analyses were run under a nitrogen atmosphere (20 mL/min).

3.5 Calculations. Blake (Freedman 1981) calculations were performed using a value of -80.227 kcal/g-mol for the heat of formation of urea, and "standard" library values for JA2 propellant.

4. RESULTS AND DISCUSSION

Screening runs of potential De-NO_x agents were performed by pyrolyzing the materials at 1,000° C. The primary basis for acceptance during screening runs was that the materials thermally decompose to generate ammonia or amines. Results of screening tests, as well as the melting (or decomposition) temperatures for the candidate De-NO_x agents, are given in Table 1. Based on the information in Table 1, it was concluded that the energetic materials (TAGN, NQ, and TATB) were unsuitable as De-NO_x agents because they generate significant quantities of NO. Ammonium carbonate was eliminated from further consideration because of its low decomposition temperature and hygroscopicity.

Table 1. Relative Pyrolysis Yields and Melting or Decomposition Temperatures for Several Candidate NO_x Agents

Compound	Relative Pyrolysis Yield		Temperature (°C)	Comments
	NH ₃ ^a	NO ^a		
Ammonium Carbonate	329	0	58 ^b	good De-NO _x agent; hygroscopic
Urea	101 ^c	0	133	good thermal stability; compatible with NC
TAGN	281	111	216 ^b	generates NO on pyrolysis
NQ	66	194	225–250 ^b	generates NO on pyrolysis
TATB	33	174	325 ^b	generates NO on pyrolysis

^a Pyrolysis at 1,000° C. Peak area determined by pyrolysis/GC-MS; sample mass = 0.3 mg.

^b Decomposes.

^c Urea also generated significant amounts of large pyrolysis products (e.g., vapor phase urea). It is expected that under combustion conditions, even more NH₃ will be generated.

Figure 3 shows the experimental results for pyrolysis of JA2-like propellants containing urea. Levels of NO generated from pyrolysis of two different hand-mixes of JA2/urea propellants are shown, as well as results from Blake calculations for propellant with the same composition. Both the computations and experimental data indicate a trend of decreasing NO with increasing urea.

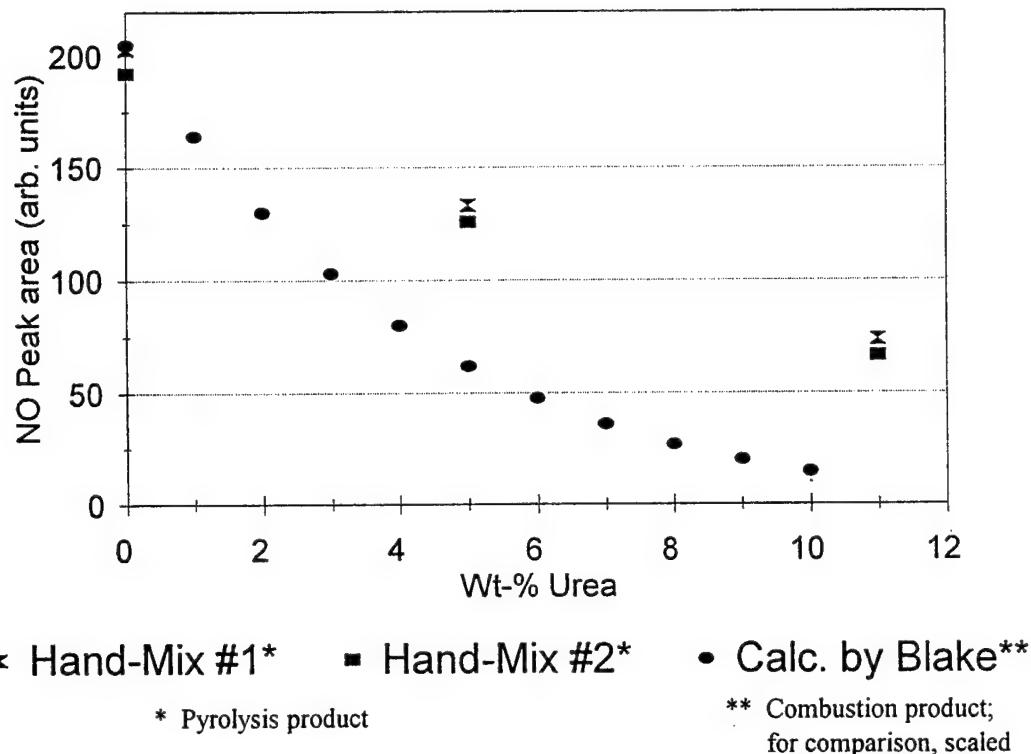


Figure 3. NO produced by JA2/urea propellant (pyrolysis products, by GC-MS, equilibrium combustion products, 0.2 g/cm^3 nominal gas phase density scaled to match NO produced at 0 wt-% urea for relative comparison).

Figures 4 and 5 show flame temperatures and impetus, respectively, calculated using the Blake code. As expected, the impetus is observed to decrease as the percentage of urea in the formulation increases. The net change in impetus for a JA2-like propellant containing 4 weight-percent urea is approximately 4% relative to neat JA2. The flame temperature of the JA2/urea propellant containing 4 weight-percent urea is approximately 200 K lower than that of neat JA2. The decrease in projectile velocity for the same JA2/urea propellant is expected to be approximately 2% (considering that muzzle velocity is proportional to the square root of the impetus).

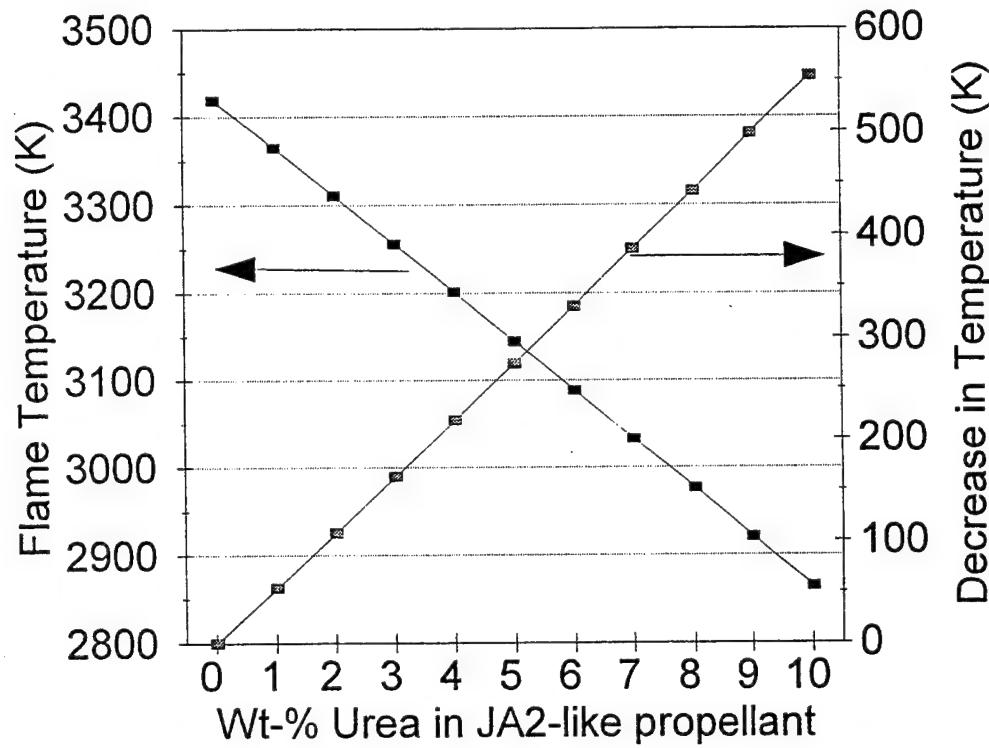


Figure 4. Calculated flame temperature for JA2/urea propellant; from Blake calculations at 0.2 g/cm^3 nominal gas phase density.

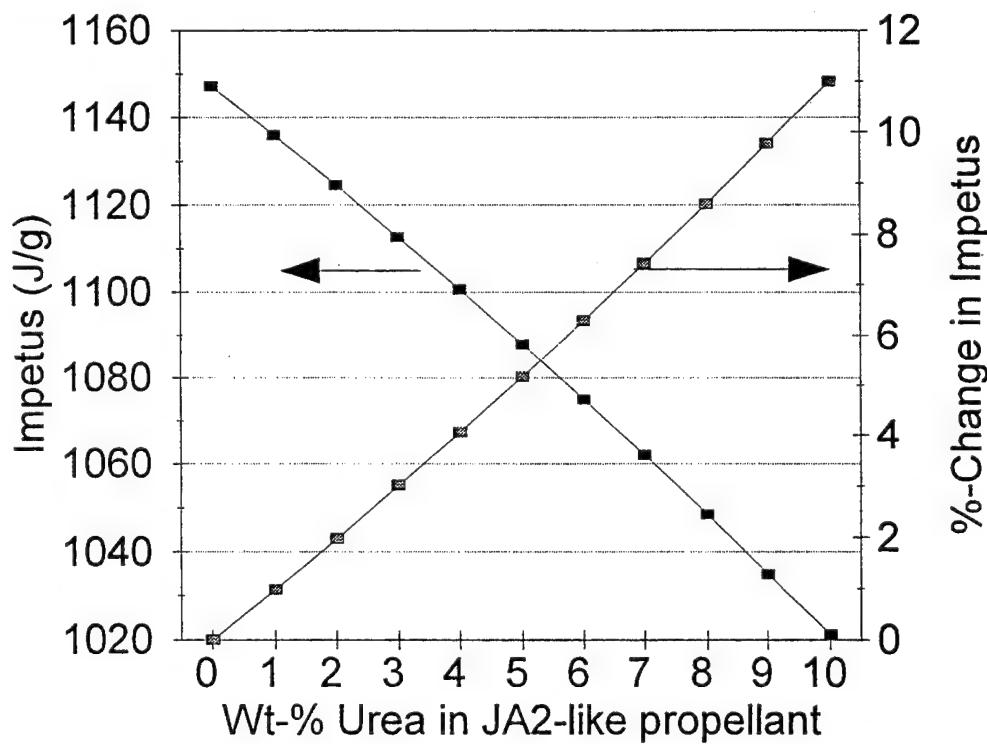


Figure 5. Calculated impetus for JA2/urea propellant; from Blake calculations at 0.2 g/cm^3 gas phase density.

The DSC thermograms presented in Figure 6 indicate that the JA2/urea formulation (7 weight-percent urea) decomposes at approximately the same temperature as does neat JA2. This result indicates that JA2 and urea are chemically compatible. This is to say that urea will not act as a catalyst in the thermal decomposition of JA2 at these heating rates. Physical compatibility has yet to be determined.

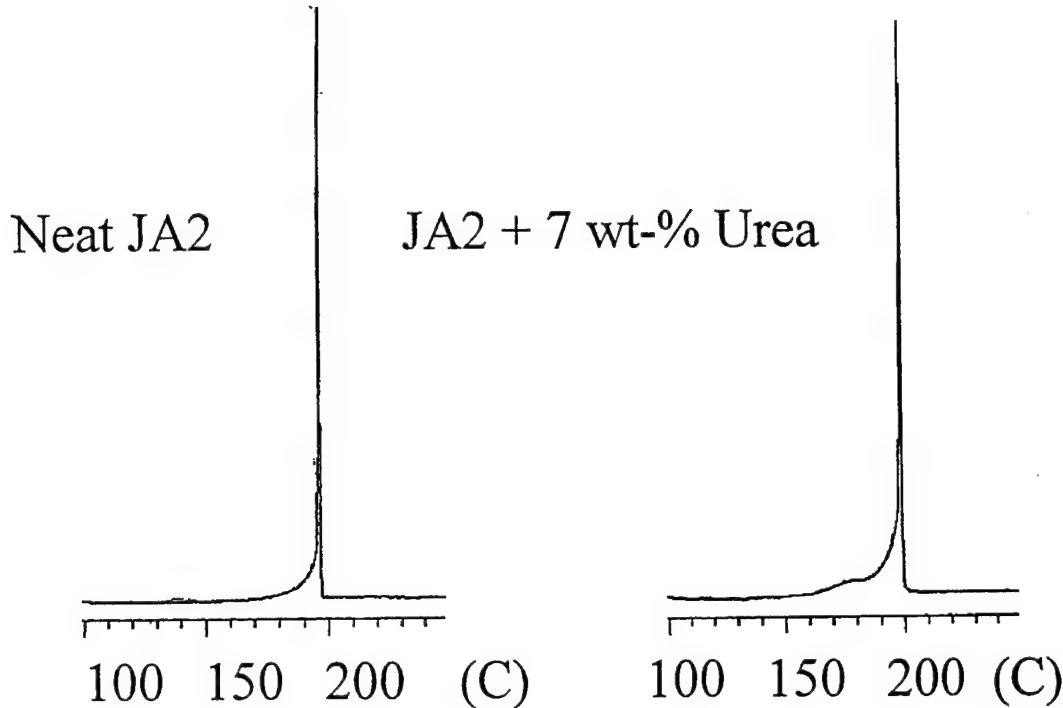


Figure 6. DSC thermograms for JA2 and JA2/urea propellant (little/no change in exotherm temperature observed, indicative of good compatibility).

5. CONCLUSION

Based on the results presented here, it is concluded that urea is an attractive De-NO_x agent: it effectively reduces the level of NO generated by pyrolysis of JA2-like propellants, yet has little effect on performance when used at low levels of incorporation. Added benefits of the use of urea as a De-NO_x agent include: (1) urea has been reported to be a successful flash suppressant (Klingenber and Heimerl 1992); and (2) urea results in flame temperature decreases that are expected to significantly extend the life of gun barrels. Results reported for the use of polyurethane additives in double-base propellants (Huwei and Ruonong 1992) suggest a similar flame temperature suppression and concomitant wear reduction.

Combined with the reduction in the production of corrosive NOx's, the reduction of flame temperature achieved by the use of urea in solid gun propellants should extend the life of gun barrels while at the same time improving air quality at R&D test centers, as well as in training and battlefield situations.

INTENTIONALLY LEFT BLANK.

6. REFERENCES

Anderson, W. R. Various private communications with members of ICB/IBC/BRL during the period of 1987-1988.

Fifer, R. A., and J. E. Cole. "Catalysts for Nitramine Propellants." US Patent 4,379,007, Disclosure submitted July 1980.

Fifer, R. A., and W. F. McBratney. "Catalysis of Nitramine Propellants by Metal Borohydrides." BRL-MR-03300, ADA, 133 215, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1983.

Freedman, E. "BLAKE - A Thermodynamics Code Based on Tiger - User's Guide and Manual." BRL-TR-02411, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1981.

Huwei, L., and F. Ruonong. "Application of Pyrolysis-Gas Chromatography in Explosive and Propellant Analysis." Journal of Beijing Institute of Technology, vol. 1, pp. 13-18, 1992.

Kaye, S. M. Encyclopedia of Explosives and Related Items, PATR-2700, vol. 8, pp. M46-M47, 1978.

Klingenber, G., and J. M. Heimerl. "Review of French Work." Gun Muzzel Blast and Flash, Progress in Astronautics and Aeronautics, vol. 139, p. 290, 1992.

Miller, J. A., and C. T. Bowman. "Mechanisms and Modeling of Nitrogen Chemistry in Combustion." Prog. Energy Combust. Sci. 15, pp. 287-338, 1989.

Rinaldi, C. U.S. Army, Advanced Field Artillery Program Manager's Office. Private communication, September 1993.

Snelson, A., K. Ase, K. Taylor, and S. Gordon. "Combustion Product Evaluation of Various Charge Sizes and Propellant Formulations." Contract No. DAMD17-88-C-8006, April 1989.

Teague, M. W., G. Singh, J. A. Vanderhoff. "Spectral Studies of Propellant Combustion. IV: Ansorption and Burn Rate Results for M43, MX39, and M10 Propellant." ARL-TR-180, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, August 1993.

Vanderhoff, J. A. "Spectral Studies of Propellant Combustion: Experimental Details and Emission Results for M30 propellant." BRL-MR-3714, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1988.

Vanderhoff, J. A. "Spectral Studies of Propellant Combustion. II. Emission and Absorption Results for M30 and HMX1 Propellant." BRL-TR-3055, U.S. Army Ballistic Research Laboratory, Aberdeen Proving ground, December 1989.

Vanderhoff, J. A. "Species Profiles in Solid Propellant Flames Using Absorption and Emission Spectroscopy." Combustion and Flame, vol. 84, pp. 73-92, 1991.

Vanderhoff, J. A., M. W. Teague, and A. J. Kotlar. "Determination of Temperature and NO Concentration Through the Dark Zone of Solid-Propellant Flames." Proceedings of the 24th Symposium (International) on Combustion, The Combustion Institute, pp. 1915-1922, 1991.

Vanderhoff, J. A., M. W. Teague, and A. J. Kotlar. "Absorption Spectroscopy Through the Dark Zone of Propellant Flames." BRL-TR-3334, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1992.

Weyandt, T. B., and C. D. Ridgeley. "Carbon Monoxide." Textbook of Military Medicine, Part III, Disease in the Environment, vol. 2, pp 397-427. Office of the Surgeon General, Department of the Army of the United States of America, R. Zajtchuk, D. P. Jenkins, and R. F. Bellamy, Eds, 1993.

Wren, D. U.S. Army Safety Center, private communication, September 1993.

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	DEFENSE TECHNICAL INFO CTR ATTN DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TP 2800 POWDER MILL RD ADELPHI MD 20783-1145

ABERDEEN PROVING GROUND

5 DIR USARL
ATTN AMSRL OP AP L (305)

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	HQDA ATTN SARD TT DR F MILTON PENTAGON WASHINGTON DC 20310-0103	2	COMMANDER US ARMY MISSILE COMMAND ATTN AMSMI RD PR E A R MAYKUT AMSMI RD PR P R BETTS REDSTONE ARSENAL AL 35809
1	HQDA ATTN SARD TT MR J APPEL PENTAGON WASHINGTON DC 20310-0103	1	OFFICE OF NAVAL RESEARCH DEPT OF THE NAVY ATTN R S MILLER CODE 432 800 N QUINCY ST ARLINGTON VA 22217
1	HQDA OASA RDA ATTN DR C H CHURCH PENTAGON ROOM 3E486 WASHINGTON DC 20310-0103	1	COMMANDER NAVAL AIR SYSTEMS COMMAND ATTN J RAMNARACE AIR 5411C WASHINGTON DC 20360
4	COMMANDER US ARMY RESEARCH OFFICE ATTN R GHIRARDELLI D MANN R SINGLETON R SHAW P O BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211	2	COMMANDER NAVAL SURFACE WARFARE CTR ATTN R BERNECKER R 13 G B WILMOT R 16 SILVER SPRING MD 20903-5000
1	DIRECTOR ARMY RESEARCH OFFICE ATTN AMXRO RT IP LIB SVCS P O BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211	5	COMMANDER NAVAL RESEARCH LAB ATTN M C LIN J MCDONALD E ORAN J SHNUR R J DOYLE CODE 6110 WASHINGTON DC 20375
2	COMMANDER US ARMY ARDEC ATTN SMCAR AEE B D S DOWNS PICATINNY ARSENAL NJ 07806-5000	2	COMMANDER NAVAL WEAPONS CTR ATTN T BOGGS CODE 388 T PARR CODE 3895 CHINA LAKE CA 93555-6001
2	COMMANDER US ARMY ARDEC ATTN SMCAR AEE J A LANNON PICATINNY ARSENAL NJ 07806-5000	1	SUPERINTENDENT NAVAL POSTGRADUATE SCHOOL DEPT OF AERONAUTICS ATTN D W NETZER MONTEREY CA 93940
1	COMMANDER US ARMY ARDEC ATTN SMCAR AEE BR L HARRIS PICATINNY ARSENAL NJ 07806-5000	3	AL LSCF ATTN R CORLEY R GEISLER J LEVINE EDWARDS AFB CA 93523-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	AFOSR ATTN J M TISHKOFF BOLLING AIR FORCE BASE WASHINGTON DC 20332	2	PRINCETON COMBUSTION RESEARCH LABS INC ATTN N A MESSINA M SUMMERFIELD PRINCETON CORPORATE PLAZA BLDG IV SUITE 119 11 DEERPARK DRIVE MONMOUTH JUNCTION NJ 08852
1	OSD SDIO IST ATTN L CAVENY PENTAGON WASHINGTON DC 20301-7100	3	DIRECTOR SANDIA NATL LABS DIVISION 8354 ATTN S JOHNSTON P MATTERN D STEPHENSON LIVERMORE CA 94550
1	COMMANDANT USAFAS ATTN ATSF TSM CN FORT SILL OK 73503-5600	1	BRIGHAM YOUNG UNIV DEPT OF CHEMICAL ENGINEERING ATTN M W BECKSTEAD PROVO UT 84058
1	UNIV OF DAYTON RSRCH INST ATTN D CAMPBELL AL PAP EDWARDS AFB CA 93523	1	CALIFORNIA INST OF TECH JET PROPULSION LAB ATTN L STRAND MS 233 103 4800 OAK GROVE DRIVE PASADENA CA 91109
1	NASA LANGLEY RESEARCH CTR ATTN G B NORTHAM MS 168 LANGLEY STATION HAMPTON VA 23365	1	CALIFORNIA INST OF TCHLGY ATTN F E C CULICK MC 301 46 204 KARMAN LAB PASADENA CA 91125
4	NATL BUREAU OF STANDARDS US DEPT OF COMMERCE ATTN J HASTIE M JACOX T KASHIWAGI H SEMERJIAN WASHINGTON DC 20234	1	UNIV OF CALIFORNIA LOS ALAMOS SCIENTIFIC LAB P O BOX 1663 MAIL STOP B216 LOS ALAMOS NM 87545
2	DIRECTOR LAWRENCE LIVERMORE NATL LAB ATTN C WESTBROOK W TAO MS L 282 P O BOX 808 LIVERMORE CA 94550	1	UNIV OF CA BERKELEY CHEMISTRY DEPARTMENT ATTN C BRADLEY MOORE 211 LEWIS HALL BERKELEY CA 94720
1	DIRECTOR LOS ALAMOS NATL LAB ATTN B NICHOLS T7 MS B284 P O BOX 1663 LOS ALAMOS NM 87545	1	UNIV OF CA SAN DIEGO ATTN F A WILLIAMS AMES B010 LA JOLLA CA 92093

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	UNIV OF CA SANTA BARBARA QUANTUM INST ATTN K SCHOFIELD M STEINBERG SANTA BARBARA CA 93106	1	THE JOHNS HOPKINS UNIV CPIA ATTN T W CHRISTIAN 10630 LITTLE PATUXENT PKWY SUITE 202 COLUMBIA MD 21044-3200
1	UNIV OF COLORADO AT BOULDER ENGINEERING CTR ATTN J DAILY CAMPUS BOX 427 BOULDER CO 80309-0427	1	UNIV OF MICHIGAN GAS DYNAMICS LAB ATTN G M FAETH AEROSPACE ENGNRNG BLDG ANN ARBOR MI 48109-2140
3	UNIV OF SOUTHERN CA DEPT OF CHEMISTRY ATTN R BEAUDET S BENSON C WITTIG LOS ANGELES CA 90007	1	UNIV OF MINNESOTA DEPT OF MECHNCL ENGNRNG ATTN E FLETCHER MINNEAPOLIS MN 55455
1	CORNELL UNIV DEPT OF CHEMISTRY ATTN T A COOL BAKER LAB ITHACA NY 14853	4	PENNSYLVANIA STATE UNIV DEPT OF MECHNCL ENGNRNG ATTN K KUO M MICCI S THYNELL V YANG UNIVERSITY PARK PA 16802
1	UNIV OF DELAWARE CHEMISTRY DEPT ATTN T BRILL NEWARK DE 19711	2	PRINCETON UNIV FORRESTAL CAMPUS LIB ATTN K BREZINSKY I GLASSMAN P O BOX 710 PRINCETON NJ 08540
1	UNIV OF FLORIDA DEPT OF CHEMISTRY ATTN J WINEFORDNER GAINESVILLE FL 32611	1	PURDUE UNIV SCHL OF AERO & ASTRO ATTN J R OSBORN GRISSEOM HALL WEST LAFAYETTE IN 47906
3	GEORGIA INST OF TECHLGY SCHOOL OF AEROSPACE ENGINEERING ATTN E PRICE W C STRAHLE B T ZINN ATLANTA GA 30332	1	PURDUE UNIV DEPT OF CHEMISTRY ATTN E GRANT WEST LAFAYETTE IN 47906
1	UNIV OF ILLINOIS DEPT OF MECH ENG ATTN H KRIER 144MEB 1206 W GREEN ST URBANA IL 61801	2	PURDUE UNIV SCHL OF MECHANICAL ENGNRNG ATTN N M LAURENDEAU S N B MURTHY TSPC CHAFFEE HALL WEST LAFAYETTE IN 47906

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	RENSSELAER POLYTCHNC INST DEPT OF CHEMICAL ENGNRG ATTN A FONTIJN TROY NY 12181	1	GENERAL APPLIED SCIENCE LABS INC 77 RAYNOR AVE RONKONKAMA NY 11779-6649
1	STANFORD UNIV DEPT OF MECHNCL ENGNRNG ATTN R HANSON STANFORD CA 94305	1	GENERAL ELECTRIC ORDNANCE SYSTEMS ATTN J MANDZY 100 PLASTICS AVE PITTSFIELD MA 01203
1	UNIV OF TEXAS DEPT OF CHEMISTRY ATTN W GARDINER AUSTIN TX 78712	1	GENERAL MOTORS RSCH LABS PHYSICAL CHEMISTRY DEPT ATTN T SLOANE WARREN MI 48090-9055
1	VA POLYTECH INST AND STATE UNIV ATTN J A SCHETZ BLACKSBURG VA 24061	2	HERCULES INC ATTN W B WALKUP E A YOUNT P O BOX 210 ROCKET CTR WV 26726
1	APPLIED COMBSTMN TECHLGY ATTN A M VARNEY P O BOX 607885 ORLANDO FL 32860	1	HERCULES INC ATTN R V CARTWRIGHT 100 HOWARD BLVD KENVIL NJ 07847
2	APPLIED MECHANICS REVIEWS ASME ATTN R WHITE & A WENZEL 345 E 47TH ST NEW YORK NY 10017	1	ALLIANT TECHSYSTEMS INC ATTN R E TOMPKINS MN 11 2720 600 SECOND ST NORTH HOPKINS MN 55343
1	TEXTRON DEFENSE SYSTEMS ATTN A PATRICK 2385 REVERE BEACH PKWY EVERETT MA 02149-5900	1	IBM CORPORATION RESEARCH DIVISION ATTN A C TAM 5600 COTTLE RD SAN JOSE CA 95193
1	BATTELLE TWSTIAC 505 KING AVE COLUMBUS OH 43201-2693	1	IIT RESEARCH INST ATTN R F REMALY 10 WEST 35TH ST CHICAGO IL 60616
1	COHEN PROFESSIONAL SVCS ATTN N S COHEN 141 CHANNING ST REDLANDS CA 92373	1	LOCKHEED MIS & SPACE CO ATTN GEORGE LO 3251 HANOVER ST DEPT 52 35 B204 2 PALO ALTO CA 94304
1	EXXON RESEARCH & ENG CO ATTN A DEAN ROUTE 22E ANNANDALE NJ 08801		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	OLIN ORDNANCE ATTN V MCDONALD LIB P O BOX 222 ST MARKS FL 32355-0222	3	THIOKOL CORPORATION WASATCH DIVISION ATTN S J BENNETT P O BOX 524 BRIGHAM CITY UT 84302
1	PAUL GOUGH ASSOCIATES INC ATTN P S GOUGH 1048 SOUTH ST PORTSMOUTH NH 03801-5423	1	UNITED TECHNOLOGIES RESEARCH CTR ATTN A C ECKBRETH EAST HARTFORD CT 06108
1	HUGHES AIRCRAFT CO ATTN T E WARD 8433 FALLBROOK AVE CANOGA PARK CA 91303	1	UNITED TECHNOLOGIES CORP CHEMICAL SYSTEMS DIV ATTN R R MILLER P O BOX 49028 SAN JOSE CA 95161-9028
1	SCIENCE APPLICATIONS INC ATTN R B EDELMAN 23146 CUMORAH CREST WOODLAND HILLS CA 91364	1	UNIVERSAL PROPULSION CO ATTN H J MCSPADDEN 25401 NORTH CENTRAL AVE PHOENIX AZ 85027-7837
3	SRI INTERNATIONAL ATTN G SMITH D CROSLEY D GOLDEN 333 RAVENSWOOD AVE MENLO PARK CA 94025	1	VERITAY TECHLGY INC ATTN E B FISHER 4845 MILLERSPORT HWY EAST AMHERST NY 14051-0305
1	STEVENS INST OF TECH DAVIDSON LAB ATTN R MCALEVY III HOBOKEN NJ 07030	1	FREEDMAN ASSOCIATES ATTN E FREEDMAN 2411 DIANA RD BALTIMORE MD 21209-1525
1	SVERDRUP TECHLGY INC LERC GROUP ATTN R J LOCKE MS SVR 2 2001 AEROSPACE PARKWAY BROOK PARK OH 44142	6	ALLIANT TECHSYSTEMS INC ATTN C CANDLAND L OSGOOD R BECKER J BODE R BURETTA M SWENSON 600 SECOND ST NE HOPKINS MN 55343
1	SVERDRUP TECHLGY INC ATTN J DEUR 2001 AEROSPACE PARKWAY BROOK PARK OH 44142	1	DIRECTOR US ARMY BENET LABS ATTN AMSTA AR CCB T SAM SOPOK WATERVLIET NY 12189
3	THIOKOL CORPORATION ELKTON DIVISION ATTN R BIDDLE R WILLER TECH LIB P O BOX 241 ELKTON MD 21921		

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND

36 DIR USARL
ATTN: AMSRL-WT-P, A HORST
AMSRL-WT-PC,
R A FIFER
B E FORCH
G F ADAMS
W R ANDERSON
R A BEYER
S W BUNTE
C F CHABALOWSKI
K P MCNEILL-BOONSTOPPEL
A COHEN
R CUMPTON
R DANIEL
D DEVYNCK
N F FELL
J M HEIMERL
B HOMAN
A J KOTLAR
W F MCBRATNEY
K L MCNESBY
N E MEGHER
M S MILLER
A W MIZOLEK
J B MORRIS
J E NEWBERRY
S A NEWTON
R A PESCE-RODRIGUEZ
B M RICE
L SEGER
P V SHARMILA
R C SAUSA
M A SCHROEDER
W TEAGUE
J A VANDERHOFF
D VENIZELOS
A WHREN
C WILLIAMSON

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1072 (Pesce-Rodriguez) Date of Report April 1996

2. Date Report Received _____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

Organization _____

CURRENT
ADDRESS

Name _____

Street or P.O. Box No. _____

City, State, Zip Code _____

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

Organization _____

OLD
ADDRESS

Name _____

Street or P.O. Box No. _____

City, State, Zip Code _____

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)